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Evaluation of Helmet Retention Systems Using a Pendulum Device

By

Peter Vyrnwy-Jones
Charles R. Paschal, Jr.
Ronald W. Palmer

Biodynamics Research Division

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United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama 36362-5292

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Dennis F. Shanahan

DENNIS F. SHANAHAN
LTC, MC
Director, Biodynamics
Research Division

J. D. LaMothe

J. D. LaMOTHE, Ph.D.
Colonel, MS
Chairman, Scientific
Review Committee

Released for publication:

David H. Karney

DAVID H. KARNEY
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Three methods were evaluated for testing the retention and rotation characteristics of aircrew helmets. Two of these employed static techniques with an anthropometric headform and human subjects. Unfortunately, though simple in execution, these tests were insensitive to the mass and mass distribution of the helmets. However, the third method, the pendulum beam Department of Transportation testing device proved to be a simple and efficient means of differentiating between the various helmets. This method should have a role in the development and testing of future U.S. Army aircrew helmets.

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Introduction

A major function of the aircrew helmet is to protect the wearer's head from injuries during a crash sequence. Unpublished data from recent simulated "crash" tests conducted at the U.S. Army Aeromedical Research Laboratory (USAARL) have shown the current U.S. Army aircrew helmets have a tendency to rotate about the head during a crash sequence. Rotational displacement of the helmet during a crash sequence can expose the cranium allowing unprotected secondary impacts and injuries to occur. Currently, there is no established test method for assessing helmet rotational displacement during a crash sequence. This report describes and compares three new test methods for observing and measuring helmet rotational displacement under dynamic and static conditions.

Helmet loss and rotation

Helmet loss and rotation can occur for many reasons. Aerodynamic lifting force associated with high-speed ejections and certain types of parachute opening shock can pull the helmet away from the wearer's head and allow the helmet to rotate freely. One of the primary causes of helmet rotation in helicopter accidents is inertial loads as the head is accelerated or decelerated by loads transmitted through the neck occur in all types of accidents. Tangential impacts to the helmet occur frequently and are exacerbated by the large flail envelope of even the well restrained occupant. Inadequately designed suspension and retention systems, as well as poorly fitted or loosely worn helmets, are significant factors in helmet rotation and loss. The helmet must be designed to remain firmly on the head with as little rotation as possible for all potentially survivable accidents.

Data concerning helmet loss or rotation

The bulk of the available data concerning aircrew helmet loss or rotation has been derived from information obtained by the U.S. Army which maintains a comprehensive database concerning all accidents at the U.S. Army Safety Center (USASC), Fort Rucker, Alabama.

In 1972, the U.S. Army Aeromedical Research Laboratory (USAARL), in conjunction with the USASC, set up the Aviation Life Support Equipment Retrieval Program (ALSERP). The purpose of

this program is to evaluate the efficiency of protective equipment in the accident environment and to use these data to improve and modify equipment for future use. The ALSERP program also fulfills the U.S. Army's commitment to Air Standardization Agreement No. 61/6 (1976) which provides guidelines for the collection and analysis of data concerning aircrew helmets damaged in service. The ALSERP helmet database now has detailed information on over 400 helmets collected from 1972-1988.

The initial report utilizing the ALSERP database (Reading et al., 1984) revealed 21 percent of all helmets came off during the crash sequence. This number had been reduced to 12 percent by the time of the second report (Vyrnwy-Jones, Lanoue, and Pritts, 1988) due to some improvements in the retention system employed in the SPH-4 helmet. However, due to an improved data collection system introduced by USASC in 1983, this latter report did note that 18 percent of all helmets were recorded as having rotated on the wearer's head during the accident sequence. Certainly the reported number of helmet rotations is an underestimation as its detection depends on the presence of telltale injuries or the ability of the wearer to communicate this fact to the investigators.

An earlier U.S. Army report (Schneider and Walhout, 1962) also commented on the problem of retention with the APH-5, the Army's first protective helmet. Unfortunately, the percentages are not detailed. Peacetime statistics in recent years from the U.S. Naval Air Development Center (NADC) indicate some 8 percent of helmets worn during ejections are lost during the escape sequence or during terrain contact. A comprehensive report concerning motorcycle helmets (Hurt, Ouellet, and Thom, 1981) indicates only 5.3 percent of all helmets studied came off the head and the majority of these failures were due to neglecting to fasten the retention systems. Interestingly, two motorcycle helmets were tested in the current study and proved to be very stable, although the results are not presented in this report.

Recent work (Melvin and Alem, 1985, Vyrnwy-Jones and Pritts, 1989) has demonstrated the large flail envelopes experienced by instrumented dummies during simulated survivable crashes using energy attenuating seats and 5-point harnesses. An interesting feature of the reports is the head velocity attained: up to 49 ft/sec. As will be discussed later, such whipping actions at high velocity are more than enough to generate significant centrifugal forces on the helmets, lifting the helmet and allowing excessive rotation to occur. In accidents involving purely vertical and horizontal components, rotation may be prevented by the helmet striking the instrument panel, or the seatback on the rebound. Nevertheless, a partially displaced helmet makes the head extremely vulnerable if it experiences a tangential blow

during a secondary impact. Such multiple impacts are common, accounting for 75 percent of all damaged helmets in the most recent ALSERP report (Vyrnwy-Jones, Lanoue, and Pritts, 1988).

It is obvious a major problem exists regarding helmet retention and the current, commonly used, testing methodologies do not address this issue.

Helmet retention testing standards

The primary methods used to evaluate helmet loss or stability have been buyer judgment and a chinstrap strength-elongation test first required by the American National Standards Institute (ANSI) in 1966 for road user helmets.

The British Standards Institute (BSI) also has produced specifications for testing protective helmets (British Standards Institute, 1985). The latter specifications include a method for assessing the stability of the retention system on a specially modified headform. The apparatus used is shown in Figure 1. It tests for forward rotation of the helmet, but gives no pass or fail criteria other than if the helmet rolls off the headform. Other tests are included which cover chinstrap strength, elongation under load, abrasion, and slippage.

Such tests either fail to take account of the dynamics of torso and head movement in aircraft accidents, or ignore the effects of helmet mass. The latter point is of considerable importance, as will be discussed later. Meeting the requirements demanded by these tests, while being an excellent starting point to improved helmet retention, does not ensure the helmet will be stable and not prone to loss or rotation under field conditions.

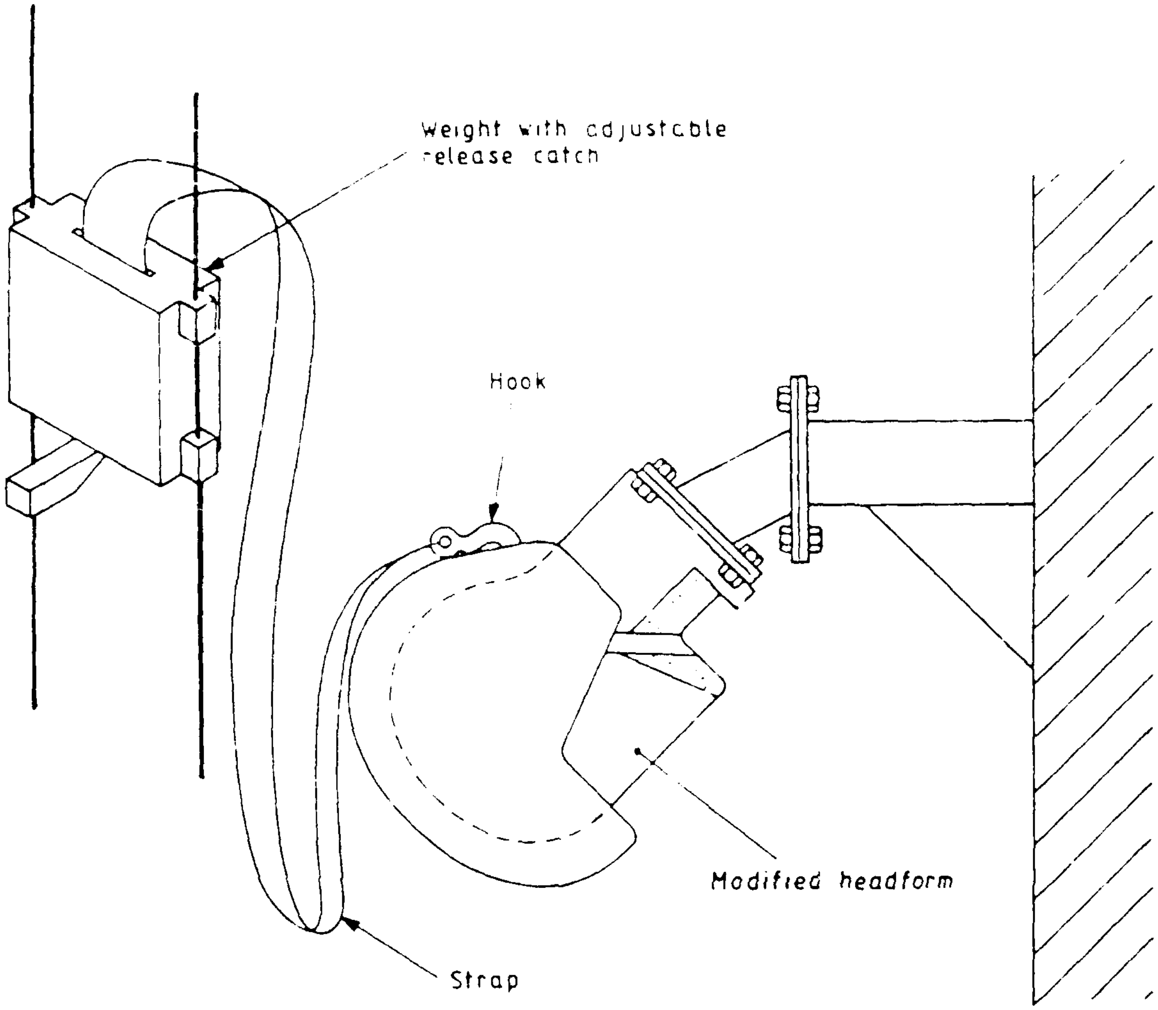

Figure 1. British Standards Institution apparatus for testing retention system effectiveness.

Helmet stability has a further role in modern aircrew helmets; they provide platforms for mounting the complex visual systems which have become a part of military aviation. These systems demand a rigid mounting platform; otherwise, the optical axis of the system will shift in flight, and force the pilot to manually readjust the helmet position, an unnecessary and potentially dangerous task.

Available testing methodology

There are several differing test methods which have been used or considered for use in evaluating the stability and efficiency of helmet retention systems. These include:

a. Use of existing sled facilities with a suitable dummy including the helmeted head. High speed film analysis of head and helmet movement would be required.

b. Drop of a helmeted headform onto a sloped or moving surface to simulate impact loads with radial and tangential vectors.

c. Deceleration of a dummy thorax with a pure vertical drop for energy and measurement the helmet's linear and rotational movement on the dummy's head and neck.

d. Simulation of the inertial load on the helmeted head/neck by deceleration of a pendulum beam as shown in Figure 2.

Discussion of the available test methods

In selecting the optimum and most practical test method two considerations apply:

a. The expense, difficulty, and repeatability of the test method.

b. Does the technique used simulate decelerative inertial loads on the helmet rather than the effect of direct impact to the helmet?

On the basis of the above observations, the pendulum beam offers the cheapest, most reliable, repeatable system. Also, it has the additional advantage of already being widely available. This test device has been in use by the Department of Transportation (DOT) to test the stiffness of the segmented neck used on the DOT (Part 572) test dummy (FMVSS 208) for more than 10 years. Some modification of the chin and nape region is required to allow smooth and realistic movement of the helmet on the head/neck interface. The major differences can be seen by reference to Figures 3 and 4 which show a standard DOT headform and the modified headform developed by USAARL. As can be seen in Figure 4, an aluminum fillet has been inserted to simulate the nape region and an aluminum chin piece covered with flexible neoprene has been added. A diagram of the headform and neck mounted to the pendulum beam is shown in Figure 5.

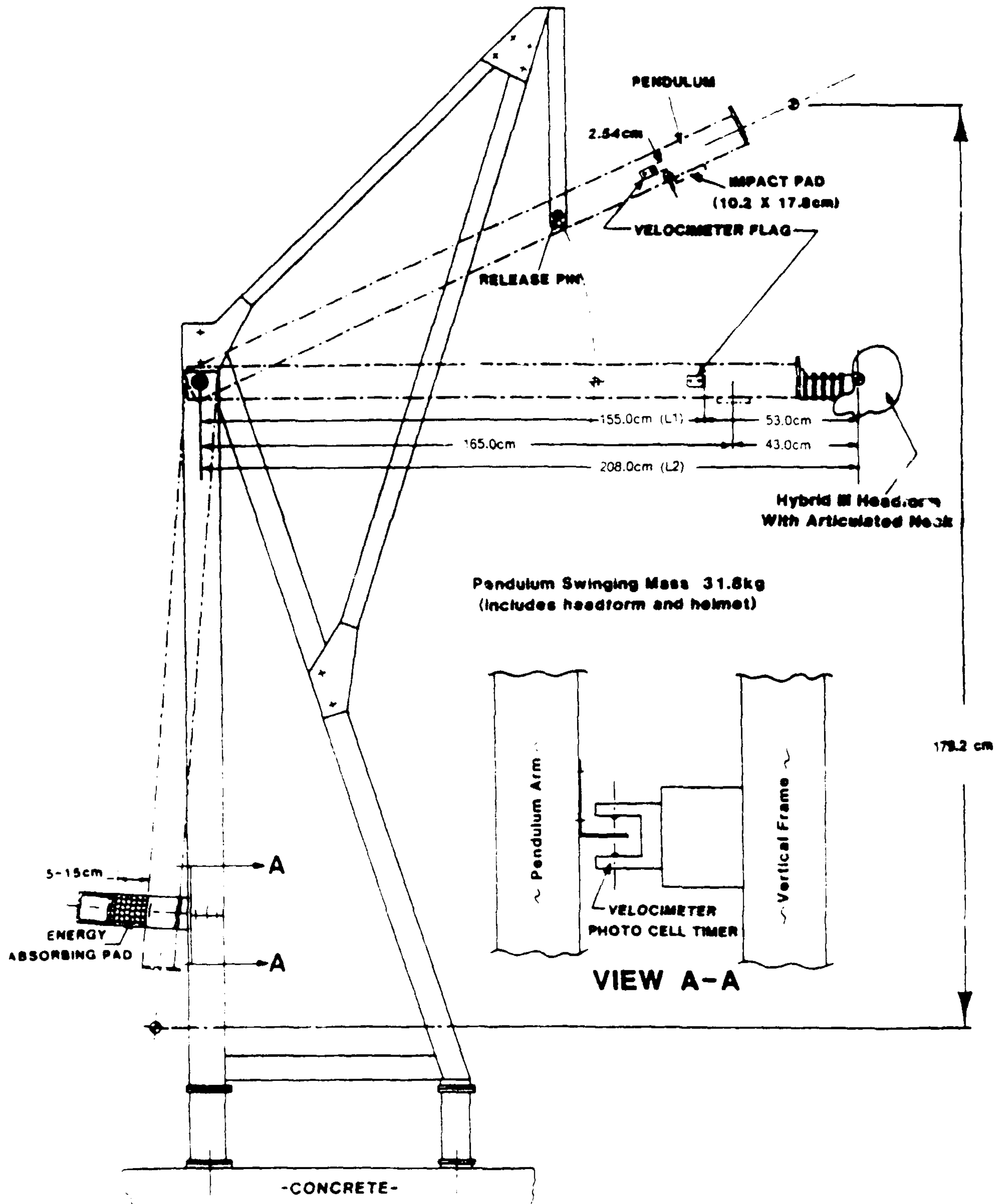

Figure 2. Helmet retention tester--pendulum impact type.

Figure 3. Standard Department of Transportation (DOT) headform.

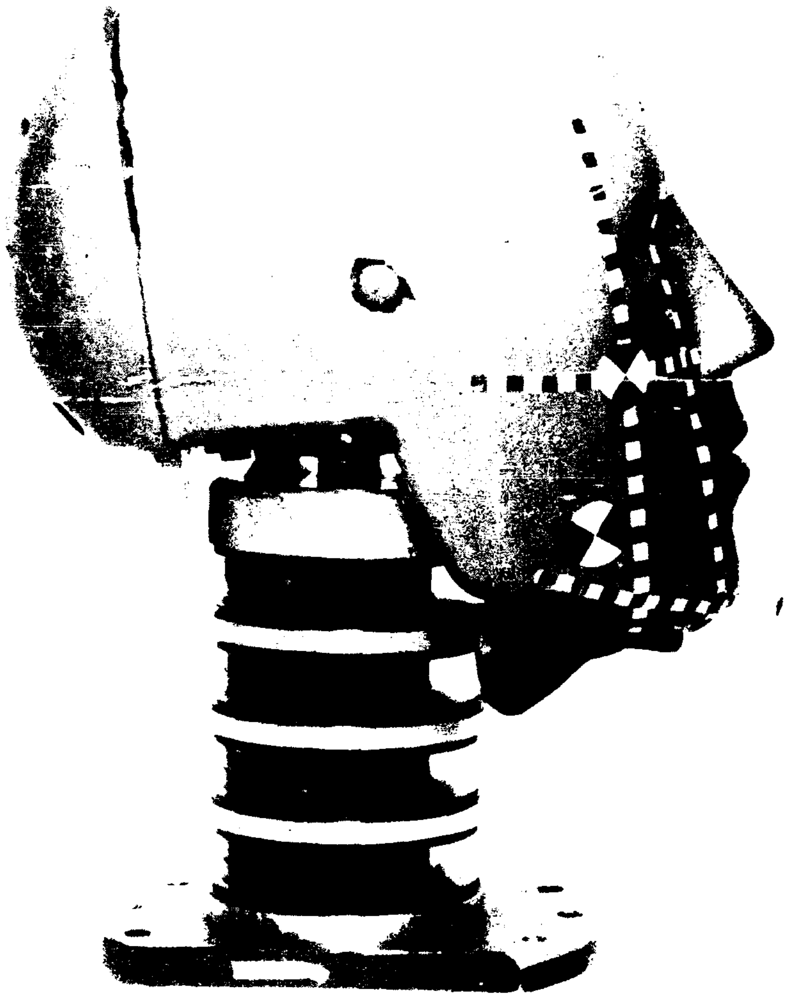

Figure 4. Modified Department of Transportation headform as used in current tests (aluminum "chin" and "nape" added).

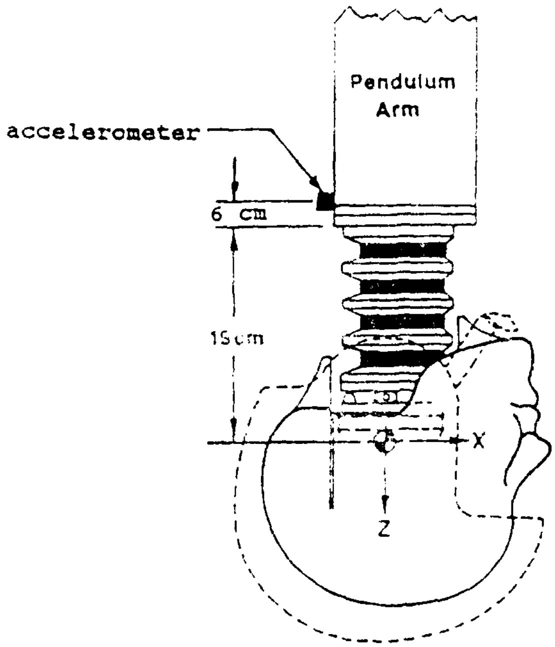

Figure 5. Modified headform as attached to the pendulum arm.

The DOT head consists of a cast magnesium cranium covered with about 1.0 cm of flexible plastic. The headform has a circumference of 58.5 cm (75th percentile), length of 20.1 cm (50th percentile), breadth of 15.6 cm (63rd percentile), and chin-to-occipital length of 26.2 cm (75th percentile). The neck consists of four neoprene segments of 2 cm thickness separated by metal disks of 0.5 cm thickness. The headform contains provision for a triaxial accelerometer located at the head center-of-gravity (CG). The standard DOT test device produces 8.3 meters per second (m/s) (27 ft/sec) maximum input velocity to the headform CG, and 1.2 to 2.4 m/s rebound velocity depending on the deceleration material used. Input velocities can be varied by adjusting the pendulum drop height.

The use of the pendulum device in helmet retention testing already has been discussed in a previous report (Gruver and Haley, 1988). Gruver and Haley discussed the feasibility of using the device and described the general principles of the methodology. Certain changes were made in the tests discussed here to ensure the techniques were standardized and the headform velocity and deceleration were nearer an average value crash pulse in lieu of the 95th percentile level used by Gruver and Haley. Improvements also have been made in the high speed film analysis and the method of digitizing the collected data.

The above system, though relatively simple to use, requires the use of expensive film or video equipment to enable digital analysis of helmet motion. In light of this, it was decided to also evaluate two less expensive and simpler methods. The first involved a simple static pull applied to a headform. The second method, similar to the first, used human subjects. The purpose for using the static pull technique was to ascertain if such a simple procedure could adequately distinguish between the various helmet retention systems.

Material and methods

DOT pendulum device

The DOT test device employed to measure head/neck response was a modified DOT pendulum. The drop height used was 179 cm as opposed to 289 cm used in the original device (Figure 2). The DOT Hybrid III headform with articulated neck was attached to the end of the pendulum arm. This arm had a length of 208 cm from the head's CG to the pendulum pivot point. The pendulum was raised and locked into position at the designated release point and then allowed to free fall to strike an energy-absorbing pad. The thickness and type of materials used for this pad have an effect on the duration and form of the deceleration applied to the articulated headform. The velocity just prior to impact was read by a velocimeter. The deceleration was measured by an accelerometer fitted to the posterior surface of the pendulum just above the attachment point of the articulated headform (see Figure 5). This was intended to give a fair approximation of the forces exerted by the harness system as it arrested torso movement, but allowed the neck and head to flail. The whole impact sequence was recorded on high speed video equipment capable of digital analysis.

Velocity of headform

A photo cell velocimeter timer* was activated by a velocimeter flag which passed through the velocimeter just prior to impact (Figure 6). The velocity was read directly from the digital display. The velocity achieved at this drop height was 5.0 m/s (16.5 ft/sec). A simple calculation provided the velocity at the CG of the headform as follows:

V1 = measured velocity = 5.1 m/s

V2 = velocity at CG of headform

From Figure 2 it can be seen V2 = V1 x L2/L1

where L1 = total arm length to the velocimeter flag = 155 cm

12 = total arm length to the CG of the headform = 208 cm

Thus, V2 = 5.0 x 208/155 = 6.7 m/s (22.1 ft/sec)

The rationale for choosing such a headform velocity was based upon data obtained from the head velocities of dummies used in simulations of survivable accidents (Melvin and Alem, 1985, Vyrnwy-Jones and Pritts, 1989). The velocity used was on the conservative side and it could be argued that a more severe test was justified. In the authors' opinion, the velocity used was sufficient for the test procedure to diagnose the displacement of various helmets.

Impact level

As explained, the impact level used simulates the likely chest deceleration experienced by a well restrained occupant during a survivable crash. Of course, the pulse can be tailored to produce any desired pattern by altering the type and thickness of the materials used as energy absorbers. In this case, a 18 cm x 10 cm piece of plasticised corrugated cardboard was bonded to a metal plate which was, in turn, backed by strips of Temperfoam™ (Figure 7).

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* See manufacturer's list, Appendix B.

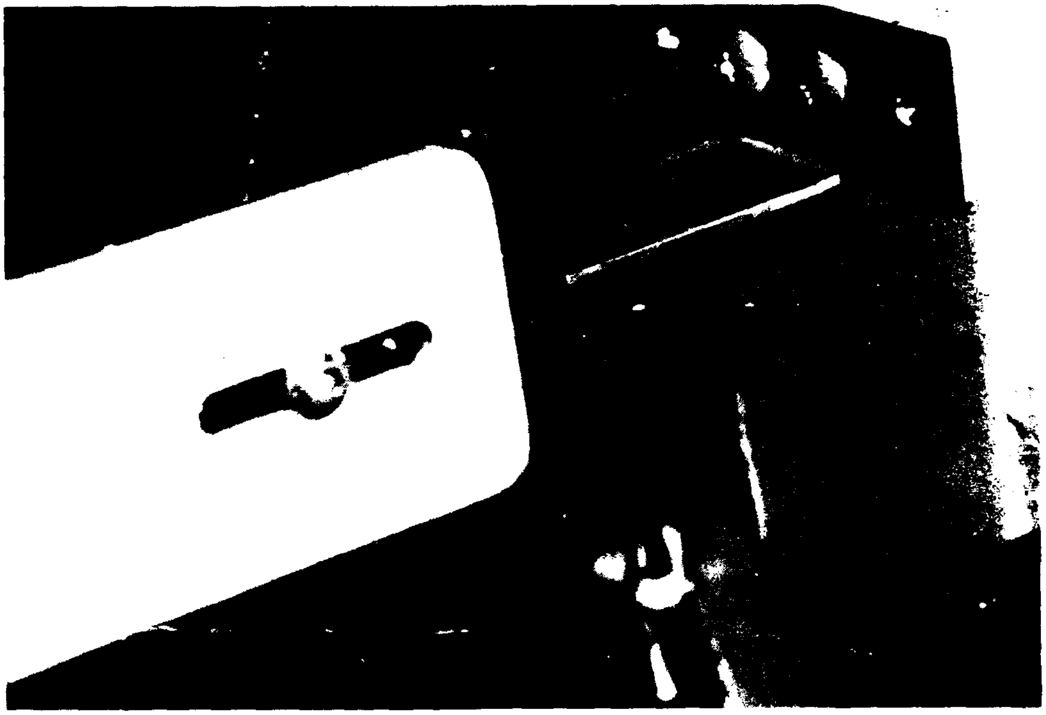


Figure 6. Velocimeter flag passing through light meter prior to pendulum impact (refer to Figure 2).

Figure 7. Paper honeycomb and plastic foam device to decelerate moving pendulum.

After some trial and error, the mixture of materials required to give a realistic and repeatable pulse was found. This pulse level was checked after each run for consistency. A typical pulse is shown in Figure 8. As can be seen, the average deceleration achieved was approximately 15 G for a total duration of about 35 milliseconds. Again, this is a very conservative figure and well within the guidelines provided for survivable accidents in the Crash Survival Design Guide (Desjardins, Laananen, and Singley, 1980). The decelerations were measured by means of an accelerometer mounted to the rear surface of the pendulum arm just superior to the mounting point of the headform (see Figure 5). The output was processed by a Nicolet 320 digital oscilloscope* and plotted on a Hewlett Packard 320 plotter*. A block diagram of the equipment used is shown in Figure 9.

In Figure 8, the pendulum arm (simulated chest) underwent an initial deceleration peak of 24 to 28 G as the temperfoam* was compressed totally and the initial crushing of the corrugated paper began. Further, note the corrugated paper maintained a crushing level of approximately 10 G after the initial "dynamic overshoot" and the total pulse duration was between 34 and 37 milliseconds. As the pendulum rebounded from the compressed paper and Temperfoam*, the helmeted headform rotated and exerted a positive acceleration to the pendulum. Also, note the helmeted headform weighed approximately 15 lb and the effective mass of the pendulum was only 20 lb, so the headform's centrifugal force was enough to accelerate the pendulum. The double accelerative pulse was caused by the headform's stop as the chin contacted the neck.

Helmet movement analysis using high speed video equipment

The entire sequence from just prior to impact to the cessation of helmet movement was recorded on a Spin Physics SP2000 motion analysis system*. Film rate was 1000 frames per second. The data were digitized directly using the reticle system provided. The equipment used is shown in Figure 10.

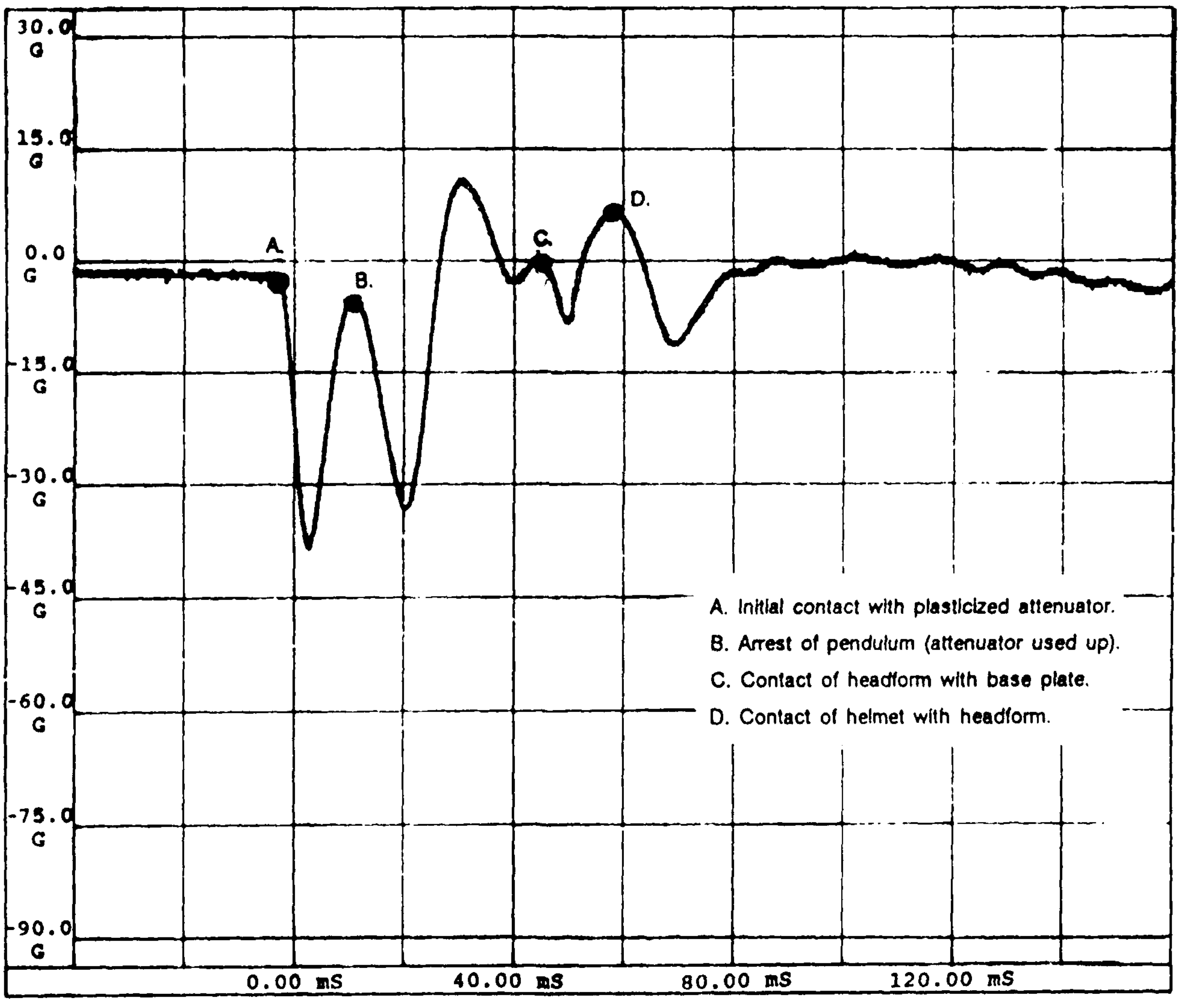


Figure 8. Typical time domain pulse for deceleration of pendulum arm.

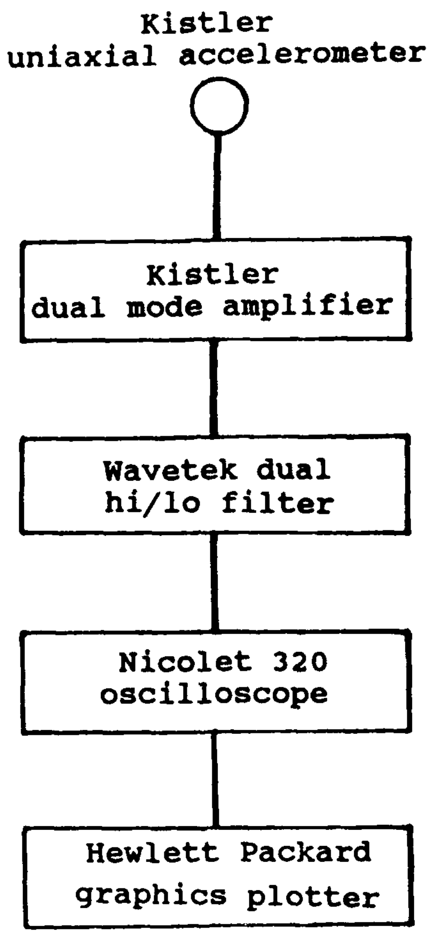


Figure 9. Block diagram of the equipment used to measure the deceleration of the pendulum arm.

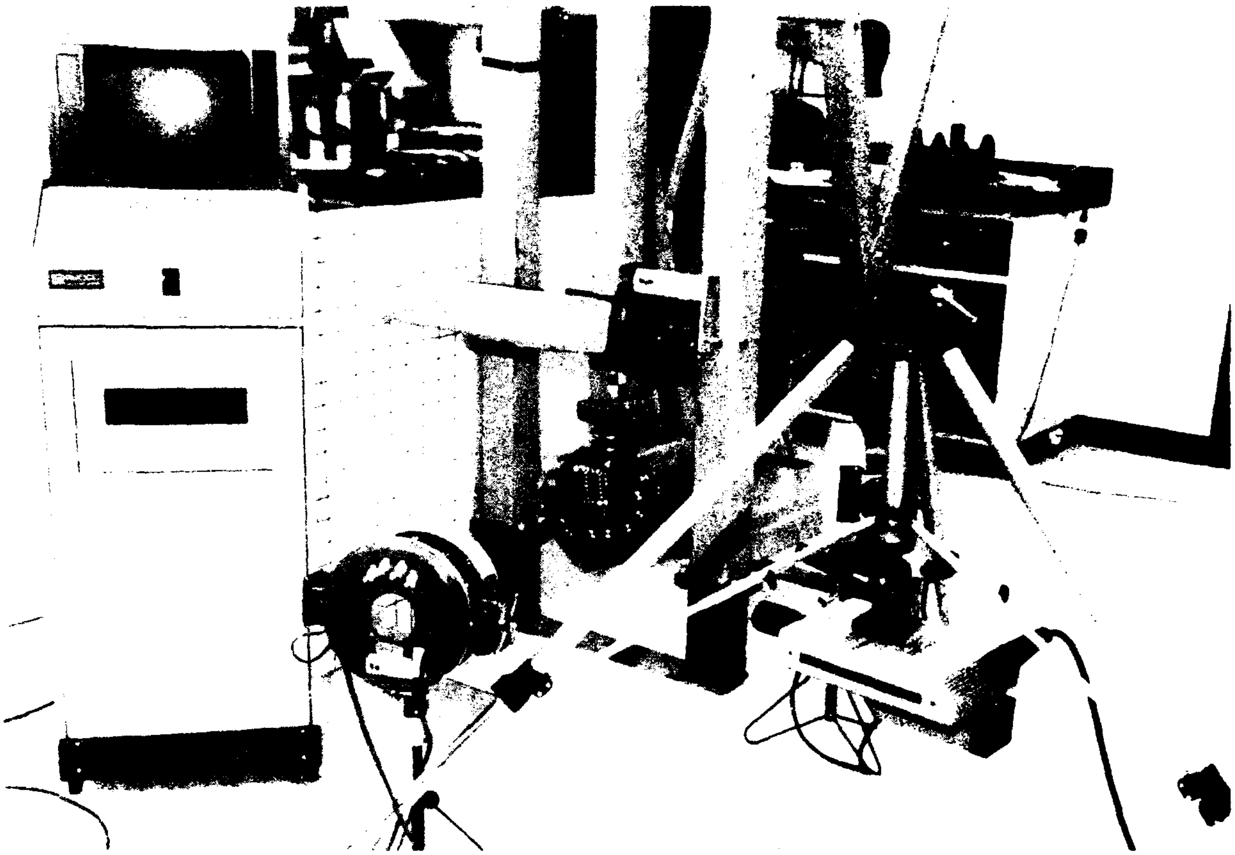


Figure 10. Motion analysis system (Spin physics SP2000) (Pendulum and lighting also shown).

In order to follow the movement of the helmet relative to the headform, the helmet and headform were marked with targets, and a marker pin was inserted into the chin of the headform (Figure 11). The following data were recorded:

a. The change in distance from the profiled tip of the helmet visor, or any such convenient marker, and the pin inserted into the headform. Any change in this distance, referred to as visor-to-chin distance (tip distance) (line d-e), Figures 12 and 13, illustrates movement of the helmet relative to the headform.

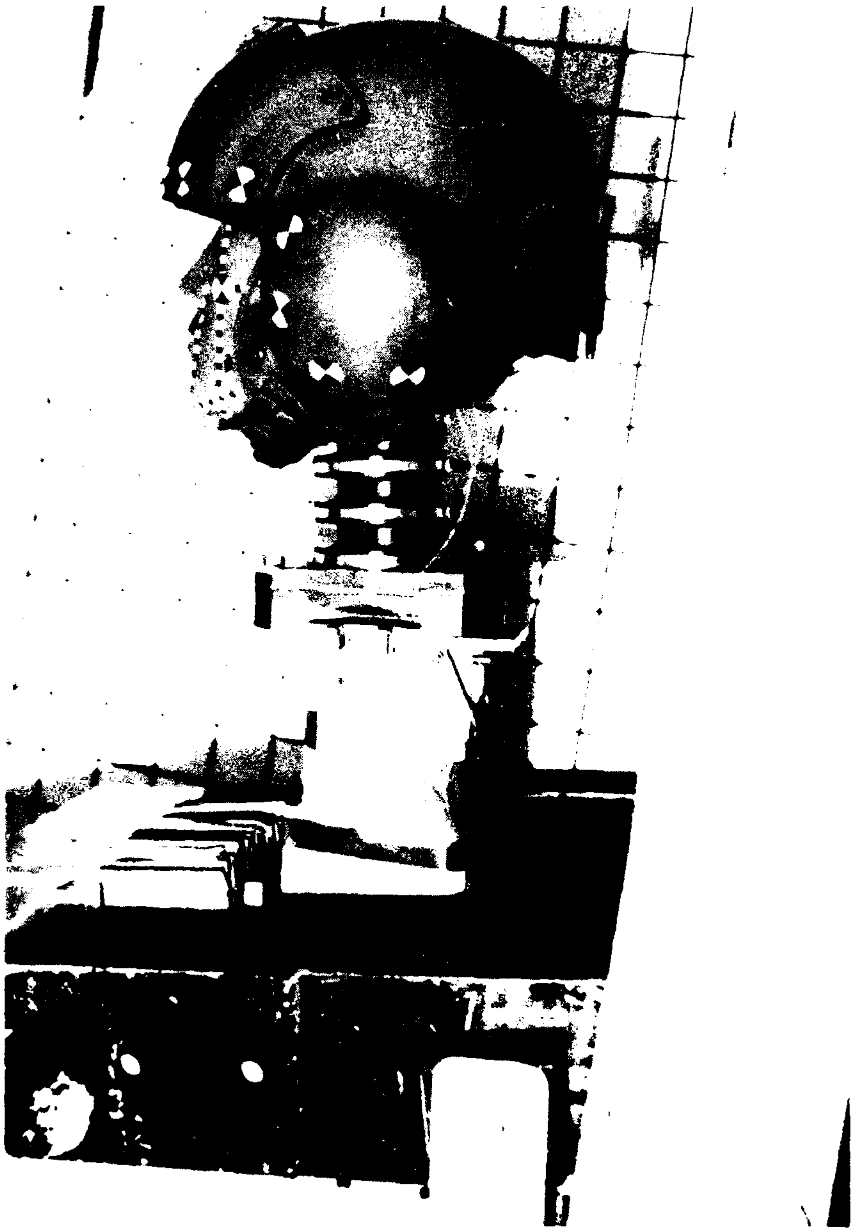


Figure 11. Targeted helmet and headform (note the target pin inserted into the chin for reference).

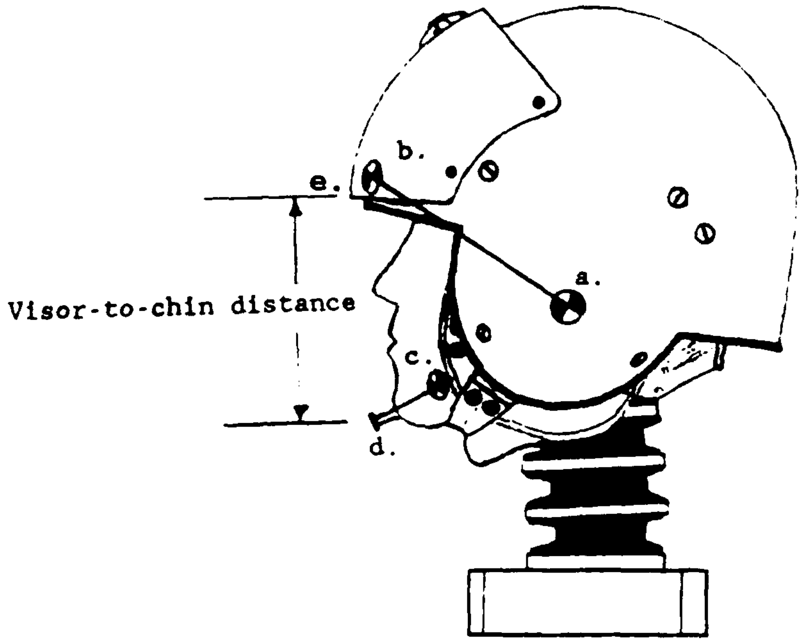


Figure 12. Resting position showing digitized points.

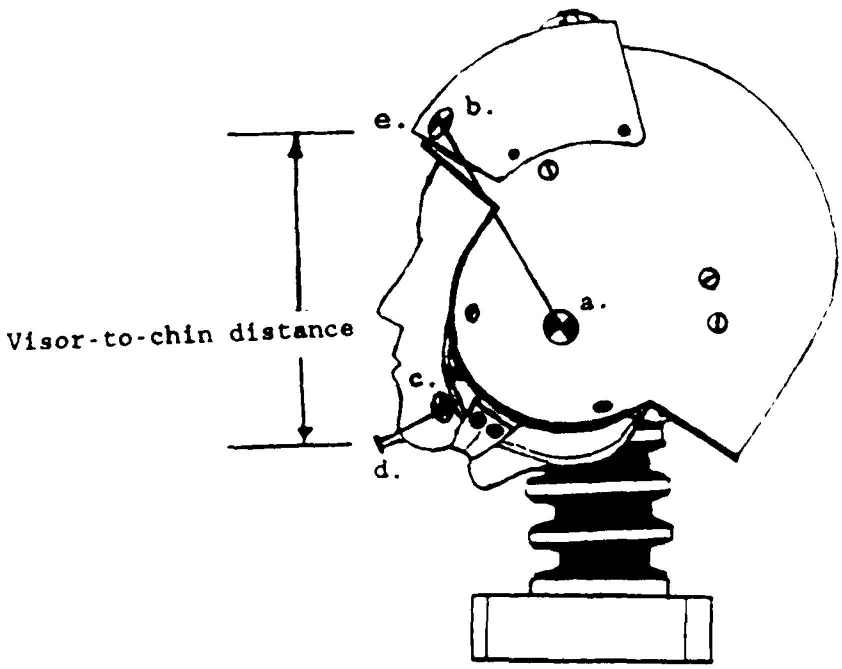


Figure 13. Rearwards movement of helmet relative to headform showing digitized points.

b. By digitizing the coordinates of any two points on the helmet and the headform, which are visible during the entire impact sequence, it is possible to record the change in relative angle between the two lines designated by the two sets of points. Figure 12 shows a typical resting position. The relative angle between the line (a-b) on the helmet is assessed relative to the line (c-d) on the headform. The change in relative angle (and visor-to-chin distance) can be seen by reference to Figure 13. This change in angle reflects the movement of the helmet on the headform.

Figure 14 demonstrates a typical impact sequence as captured by the high speed videotape equipment. There are four distinct phases to the impact sequence:

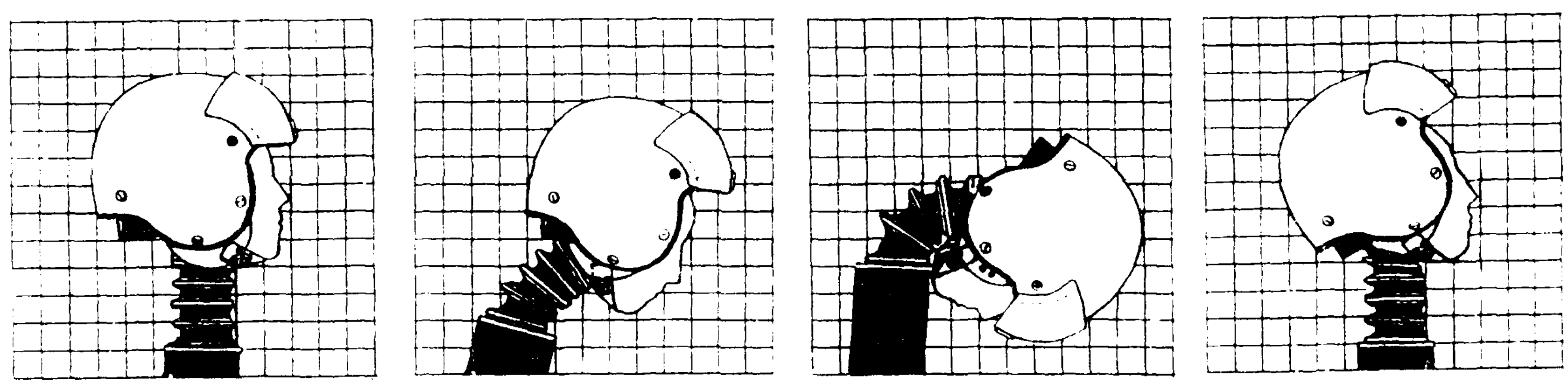
a. Initial position. This is the reference position of the helmet just prior to the impact of the pendulum device. It should be noted no movement of the helmet relative to the headform has occurred by this stage even though the headform has achieved a velocity of 22.4 ft/sec.

b. Maximum lofting. As the device decelerates upon contact with the energy-absorbing pad, the inertia of the helmet causes it to lag behind the headform. This allows the headform to rotate forward relative to the helmet. In some cases, this allows the forehead and crown of the headform to be exposed.

c. Maximum forward deflection. As the impact sequence continues, the helmet commences to rotate forward relative to the headform and, in some cases, the rotation is arrested only by the visor striking the nose of the headform.

d. Maximum rearward deflection. During the rebound sequence the helmet tends to rotate rearward relative to the headform. This rearward movement is more marked than the similar movement which occurs during the initial phases of the impact sequence.

Means for maximum lofting (angular rotation and visor-to-chin movement), maximum forward deflection (angular rotation and visor-to-chin movement), and maximum rearward deflection (angular rotation) were analyzed by analysis of variance. Means were compared using the Student-Newman-Keuls multiple range test.



Initial Position

Maximum Lofting

Maximum Forward Deflection

Maximum Rearward Deflection

Figure 14. Typical helmet impact sequence.

Chinstrap tension

In part, the stability of the helmet on the headform will depend on the amount of tension applied to the chinstrap. There were no current data available on this topic, so it was decided to carry out a small, ancillary trial to ascertain a value which could be used in the retention trials. A group of 10 helicopter pilots were selected at random. They were requested to don their helmets and adjust the chinstrap as snugly as normal. The chinstrap position was marked and then the procedure repeated except that the chinstrap was retightened to the marked position by using the simple tensiometer device shown in Figure 15. The tension required to tighten the chinstrap was recorded. The results ranged from 5.5 lb to 9 lb with a mean value of 8 lb. In the actual experiments, a value of 10 lb was used as this gave the helmet the "benefit of the doubt" and helped compensate for some of the inadequacies of the headform design.

Napestrap tension

It was not possible to repeat the above procedure in the case of the napestrap, as different helmets have varying adjustment mechanisms. A snug fit was achieved and over tightening avoided. For consistency, the same technician performed the napestrap adjustment for each test. The technique requires experience and judgment for consistent results.

Test procedure

Prior to each test, the helmet was fitted to the headform by a trained aviation life support equipment (ALSE) specialist. The chinstrap and napestrap were tensioned as described above. Visors were locked in the "up" position and loose items such as microphone booms and communication cords were taped to the helmet to avoid damage during the testing procedures. The pendulum was then raised to its drop position (Figure 2) and the lights and video equipment prepared. After release, the pendulum (chest) deceleration was recorded on the Nicolet 320 Digital Oscilloscope*. The pendulum velocity just prior to impact was recorded on the VS300 Velocimeter*.

Static procedures

Two static test procedures were employed to assess helmet retention and stability. These employed either a headform or human subjects.

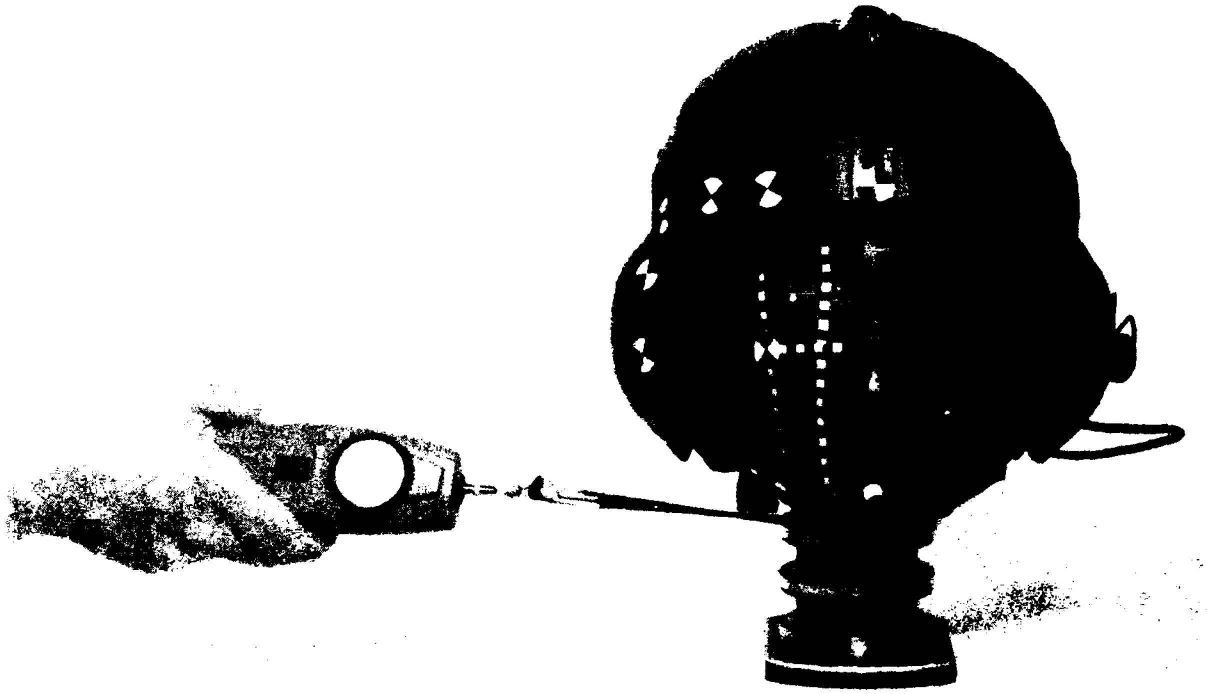


Figure 15. Scale used to measure chinstrap tension.

Static headform tests

After fitting helmets to a headform in the same manner as described for pendulum testing, a vertical pull of 25 lb was applied to the front and rear of the helmet as shown in Figures 16 and 17. The vertical distance traveled, either up or down, by the front of the helmet was measured.

Human subject tests

The procedure employed was the same as for static headform testing except that two volunteers were used. The static pull applied was 25 lb. Again, the vertical distance traveled by the front of the helmet relative to the head was recorded.

Figure 16. Vertical tension load of 25 pounds being applied to front of SPH-4 helmet.

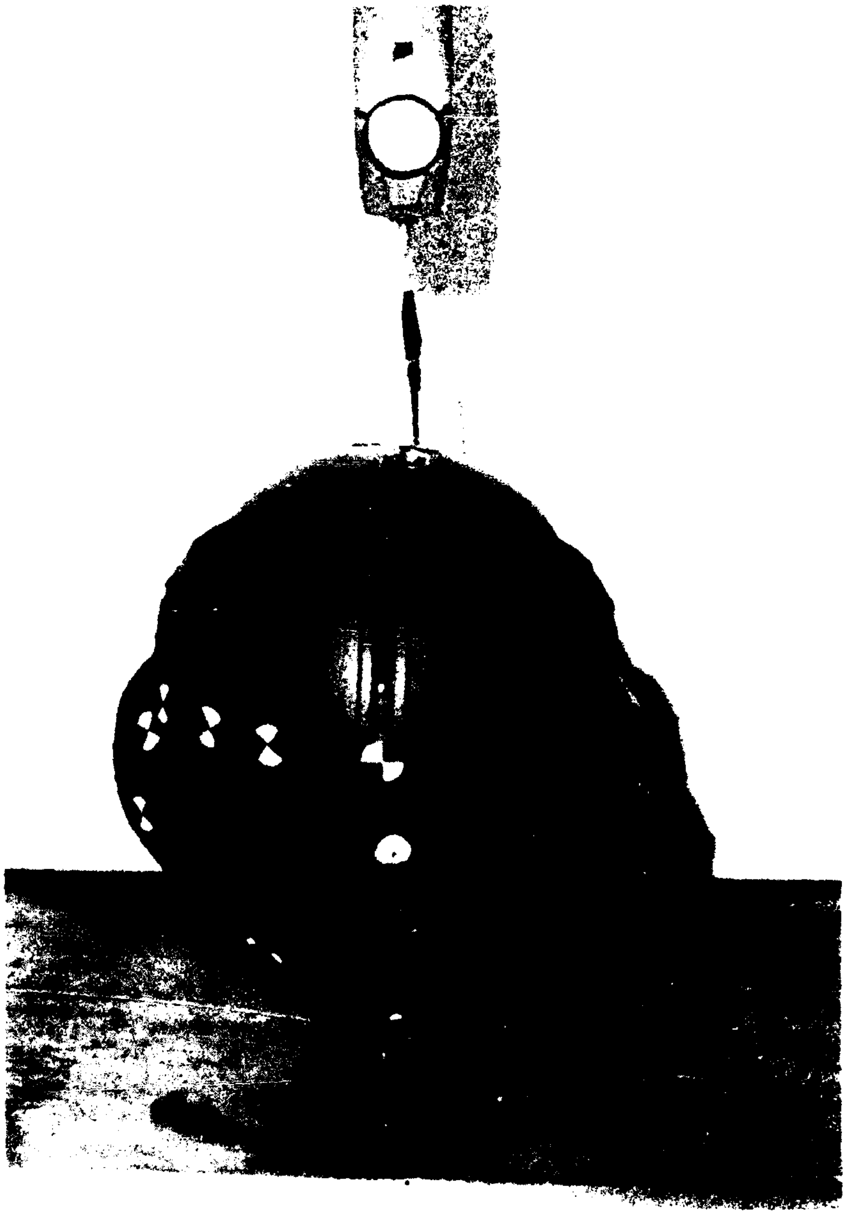


Figure 17. Vertical tension load of 25 pounds being applied to rear of SPH-4 helmet.

Helmets employed during testing procedure

The helmets used during the tests described are shown with relevant details in Table 1. During the course of the experiment, it became obvious that the standard SPH-4 with a thermoplastic liner (TPL) was particularly unstable when compared to other helmets such as the standard SPH-4 with a sling suspension and the SPH-5 with its lighter shell. In view of this undesirable feature, some trials were carried out with a modified retention system designed at USAARL, which was intended to alleviate the situation. This helmet is referred to as the SPH-4 (modified) and the major novel features are shown in Figures 18, 19, and 20. As can be seen, the standard double snap fasteners have been replaced with a double D ring and the retention system consists of a continuous yoke attached to the ear assembly and the shell. USAARL purchased 10 of the "yoke" assemblies seen in Figures 18 through 20, from Gentex Corporation, Carbondale, Pennsylvania. Gentex recommended the use of a 1.0-in wide tab attached to the nape strap and the SPH-4 shell. Our tests and analyses indicated the tab addition was worthwhile. Thus, the tab shown in Figure 20 was tested and all references to the modified "yoke" assembly include the tab as a part of the modified retention system.

Although other helmets, not shown in Table 1, were used during the course of the experimentation, it was decided that only helmets with direct relevance to Army aviation would be included in this paper.

Table 1.

Helmet descriptive data.

Component		Helmet identity					
		SPH-4	SPH-4 W/TPL	SPH-4 w/modified retention assembly	SPH-5™	HGU-55P	ALPHA™
Helmet weight (lb), complete with visor and communications		Reg 3.40	Reg 3.25	Reg 3.26	Reg 2.80	Med 2.08	Lg 2.90
Suspension type		Sling	TPL	TPL	TPL	TPL	Sling/pad
Shell material		Epoxy and fiberglass	Epoxy and fiberglass	Epoxy and fiberglass	Epoxy and KEVLAR™	Epoxy and fiberglass	Polyester and KEVLAR™
Liner foam	Material	Polystyrene	Polystyrene	Polystyrene	Polystyrene	Polystyrene	Polyurethane
	Density (lb/ft^3)	4.50	2.50	2.50	2.50	3.00	4.50
	Thickness (in)	0.50	0.63	0.63	0.63	0.50	0.75
Retention harness type		Chinstrap-to-earcup-to shell	Chinstrap-to-earcup-to shell	Continuous yoke shell-chinstrap Nape-shell tab	Chinstrap-to-earcup-to shell	Separate nape and chinstrap	Chinstrap-to-shell
Napestrap type		Napestrap-to-earcup-to-chinstrap	Napestrap-to-earcup-to-chinstrap	Napestrap-to yoke	Napestrap-to-earcup-to-chinstrap	To shell	Napestrap-to-shell
Chinstrap strength (lb)		280	280	440	280	150	450
Chinstrap release type		2 snaps	2 snaps	Double D-ring	2 snaps	Single snap	Male to female quick release

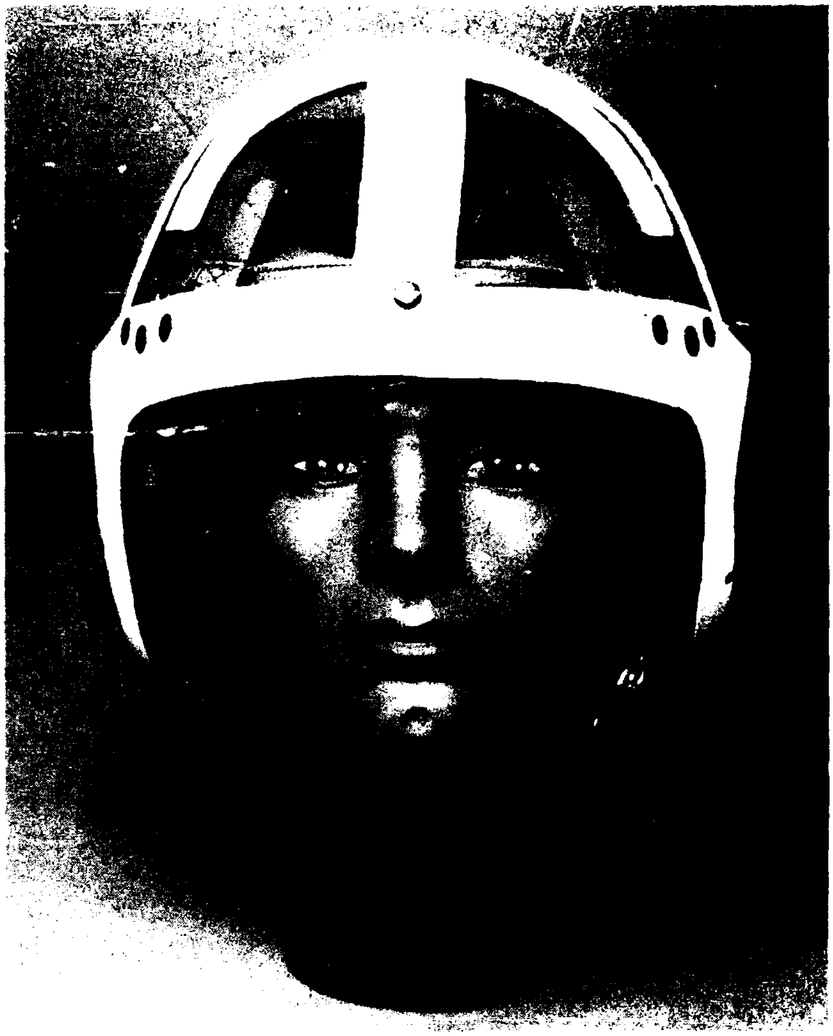


Figure 18. Modified yoke retention system installed in cut-away SPH-4 helmet (Note tab-type "D" ring release).

Figure 19. Modified yoke retention system installed in cut-away SPH-4 helmet (Note position of rear half of yoke).

Figure 20. Close-up view of modified yoke retention system (Note the shell attachment tab at nape overlap area).

Results

The results are presented in three sections which refer, respectively, to the pendulum dynamic testing and the two static procedures using a headform and human subjects.

Pendulum dynamic testing

The test methods employed here obviously evolved during the process of refinement natural to any such experimentation. The results quoted refer to the mean values obtained during a series of tests, where the experimenters considered the conditions obtained were fair to use in evaluating the performance of a helmet under simulated impact conditions. For instance, using talc to produce a slicked headform, thereby simulating the effects of sweat on the human head, was found to have no effect on helmet movement and hence talc was not employed during these trials. Off-axis loads obtained by rotating the headform to the left or right in the yaw direction produced less helmet movement than the equivalent impact in the fore-aft direction, and because of this, only the latter (sagittal plane) vector was employed.

Table 2 presents the performance data of the pendulum device itself. As can be seen in this table, there was little variation observed in the average velocity of the pendulum beam. On the other hand, peak G showed the most variation. Probably, this is due to variability in the plasticized-paper energy attenuators used.

Tables A-1 to A-3 in Appendix A list the results for seven types of helmets, four of which are variations of the SPH-4 series helmet. The results refer to mean values obtained from a series of two-to-three tests on each helmet type.

Before we began this experiment, we hypothesized that measurement of linear displacment during lofting would be the most consistent and useful indicator of helmet retention performance. We reasoned if the head rotated away from the helmet, then the liner would lose contact with the head. Therefore, the helmet would be secured by the chinstrap alone, permitting the helmet to freely move forward or rearward on the head. The degree of this movement would be dependent upon the elasticity of the retention material and upon the ability of the helmet's napestrap or napeplate to firmly grip the nape area or, more simply, friction. As expected, the visor-to-chin movement during lofting showed much less variation within helmet type than the other measured parameters (see Table A-2).

Table 2.

Pendulum performance statistics.

Parameter	N	Mean	Variance	Coefficient of variation
Velocity (f/s)	46	16.48	0.30	1.15
Peak duration (ms)	53	34.50	4.90	6.38
Average G	53	14.76	0.90	6.41
Peak G	53	29.03	12.76	12.30

Headform static testing

Tables A-4 and A-5 show the distances moved by a reference point on the visor relative to a fixed reference point on the headform (Figures 16 and 17). The 25 lb vertical pull was applied to the front and rear of the helmet.

Human static testing

Tables A-6 and A-7 show the distances moved by a reference point on the visor relative to a fixed reference point on the chin of two human volunteers used in this trial. The technique used is similar to the static headform testing. However, there were so many drawbacks to such a method that only two subjects were employed before the technique was abandoned as impractical.

Discussion

Pendulum dynamic testing

The pendulum dynamic testing method proved to be the most reliable of the three methods tested. It was the only method by which we could actually ascertain differences between the retention performances of different helmet types. However, the method has a number of potential drawbacks that should be addressed. They are:

a. Only inertial loads were applied as opposed to any direct helmet impacts.

b. A centrifugal force of 2.3 G and a gravitational force of 1.0 G was applied to the helmet just prior to impact. These forces are additive and tend to lift the helmet away from the fixed headform and reduce the frictional contact of the helmet liner with the headform.

c. The design of the headform is less than ideal and some improvements to the nape and chin area, as well as headform anthropometry, would be desirable.

d. Fitting of the helmet to the headform is difficult, there being no subjective feedback of comfort from the headform. Therefore, the procedure must rely on user experience and data obtained from human trials, as was done for chinstrap tension in this case.

Direct observation of helmeted dummy data from simulated crashes (USAARL unpublished data) indicates considerable helmet movement does occur without any direct helmet impact. This confirms the data from ALSERP which, as already discussed, shows a high incidence of helmet rotation during actual accidents.

The 3.3 G lifting force is a minor problem but, as discussed, very little movement was noted prior to the pendulum impact. Many helicopter accidents present complex kinematics and it is felt the test conditions employed provide a worst case condition. These reinforce the actual data obtained. Obviously, it would be possible to simply orient the pendulum device to impact with the helmet in an upright position. However, this would entail the alteration of a widely available piece of testing equipment.

The design of a totally realistic humanoid headform would be beneficial to any helmet retention testing program. However, it is felt the current modified device is sufficient for the comparison of various helmet types. Only broad trends in helmet retention performance can be noted and the current equipment seems sufficient for this purpose. Finally, the test conditions used are well within the defined parameters of a survivable accident (Desjardins, Laananen, and Singley, 1980) and, justifiably, could have been made more severe.

Headform static testing

Reference to Figures 3 to 6 establishes the technique, but does not indicate the differences between the SPH-5 helmet and the SPH-4 helmet equipped with TPL. This almost certainly is due to the lack of sensitivity of this test method to the mass of the helmet shell. The 25-lb vertical pull used is a purely arbitrary value and bears no relation to any simulated impact conditions.

It was decided not to continue with further static headform testing due to the inability to differentiate between the performance of the SPH-4 with TPL and the SPH-5 helmet with this test.

Human static testing

Although at first sight this would appear to be the most realistic of the two static techniques employed, there are a number of overriding objections which render the technique totally impractical for helmet testing.

a. A supply of subjects with suitable and identical anthropometric measurements would be required at all testing establishments.

b. Medical monitoring of all tests would be required and each subject would need a radiological and orthopedic evaluation prior to testing.

c. It is very difficult for the subject to maintain his head in a stable position while the vertical pull is applied.

d. The method suffers from the same disadvantages as the static headform technique.

Considering all these points, it was decided not to pursue human testing.

Conclusions

The main conclusions to be drawn are:

a. Static pull tests for assessing helmet stability are not sensitive to the mass or mass distribution of helmets and should not be used alone in their testing.

b. Shell mass and mass distribution have a major effect on helmet rotation during the impact sequence.

c. Tests for helmet rotation during impact are only part of a wider series of tests. The test cannot be used in isolation, only as part of a comprehensive test scheme which includes impact performance, chinstrap and retention system strength.

d. Ideal retention and prevention of rotation is best achieved by:

(1) A close fitting suspension system which is integrated with the retention system. It should allow minimal stretch of retention material and minimal compression of

suspension material, or movement of the helmet either forward or rearward.

(2) The nape strap should prevent, as far as possible, any tendency for the helmet to rotate forward on the head. It should also maintain a firm grip on the nape area of the neck and be attached to the rear area of the shell with minimal stretch of retention material.

e. Stability of the helmet relative to the head will soon become of paramount importance with regard to the increased use of helmet mounted sighting systems and visual aids such as night vision goggles.

Recommendation

A dynamic helmet testing technique, such as the one described above, should be introduced for all U.S. Army aviation helmets.

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Appendix A.

Table A-1.

Angular rotation data.

Helmet description	N	Angle change maximum lofting (deg)	Angle change maximum forward deflection (deg)	Angle change maximum rearward deflection (deg)
SPH-4 standard	3	$22 \pm 2^{a,b}$	$15 \pm 3^{a,b}$	12 ± 6^{a}
SPH-4 4-layer TPL not form fitted	2	$27 \pm 2^{b,d}$	21 ± 3^{b}	27 ± 7^{a}
SPH-4 4-layer TPL form fitted	3	$27 \pm 2^{b,d}$	21 ± 3^{b}	34 ± 6^{a}
SPH-5 standard not form fitted	2	$23 \pm 2^{a,b}$	$15 \pm 3^{a,b}$	10 ± 7^{a}
SPH-4 w/modified yoke retention assembly	2	$15 \pm 2^{a,c}$	$16 \pm 3^{a,b}$	6 ± 7^{a}
HGU-55P standard	2	$17 \pm 2^{a,b}$	$1 \pm 3^{a,c}$	13 ± 7^{a}
ALPHA standard	3	$14 \pm 2^{a,c}$	$5 \pm 3^{a,c}$	6 ± 7^{a}

Note: Data are means $\pm$ standard error of the mean (means within column with different letters differ ($p=0.05$)).

Table A-2.

Linear displacement of helmets during lofting mean ± standard error of the mean

N	Helmet description	Movement of helmet relative to headform (in.)
2	SPH-4 standard with modified retention assembly	1.70 ± 0.19[a]
3	ALPHA	1.77 ± 0.15[a]
2	HGU-55P	1.80 ± 0.19[a]
3	SPH-4 standard	2.30 ± 0.15[a]
2	SPH-5 standard	2.95 ± 0.19[b]
3	SPH-4 4-layer TPL formfitted	3.27 ± 0.15[b]
2	SPH-4 4-layer TPL non-formfitted	3.35 ± 0.19[b]

Note: Means with different letters differ (p=0.05).

Table A-3.

Linear displacement of helmets during forward displacement mean ± standard error of the mean

N	Helmet description	Movement of helmet relative to headform (in)
2	HGU-55P	0.30 ± 0.26^a
3	ALPHA	0.50 ± 0.22^a
2	SPH-4 w/modified yoke retention assembly	1.70 ± 0.26^b
3	SPH-4 standard	1.73 ± 0.26^b
3	SPH-4 4-layer TPL formfitted	2.03 ± 0.22^b
2	SPH-5 Standard	2.05 ± 0.26^b
2	SPH-4 4-layer TPL non-formfitted	2.25 ± 0.26^b

Note: Means with different letters differ (p-0.05).

Table A-4.

Forward static pull testing
mean values.

Number of runs	Helmet description	Movement of helmet relative to headform (in)
3	SPH-4 standard	4.7
3	SPH-4 4-layer TPL non-formfitted	6.4
3	SPH-4 4-layer TPL formfitted	5.5
3	SPH-5 TPL non-formfitted	6.4
3	SPH-5 TPL formfitted	5.7

Table A-5.

Rearward static pull testing
mean values.

Number of runs	Helmet description	Movement of helmet relative to headform (in)
3	SPH-4 standard	3.2
3	SPH-4 4-layer TPL non-formfitted	6.0
3	SPH-4 4-layer TPL formfitted	4.3
3	SPH-5 TPL non-formfitted	4.6
3	SPH-5 TPL formfitted	4.4

Table A-6.

Human subject forward static pull.

Number	Helmet description	Movement of helmet relative to head (in)
2	SPH-4 standard	6.9
2	SPH-4 4-layer TPL formfitted	7.6
2	SPH-5 TPL formfitted	7.1

Table A-7.

Human subject rearward static pull.

Number	Helmet description	Movement of helmet relative to head (in)
2	SPH-4 standard	3.2
2	SPH-4 4-layer TPL formfitted	7.0
2	SPH-5 TPL formfitted	5.3

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